EFFECT OF GLASS POWDER ON THE MECHANCAL, THERMAL AND MICROSTRUCTURAL PROPERTIES OF AUTOCLAVED AERATED CONCRETE

By

TAYYAB ZAFAR

(NUST201463424MSCEE15214F)

This thesis is submitted in partial fulfilment of
the requirements for the degree of

Master of Science

in

Structural Engineering

National Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

2018

This is to certify

that Thesis entitled

EFFECT OF GLASS POWDER ON THE MECHANCAL, THERMAL AND MICROSTRUCTURAL PROPERTIES OF AUTOCLAVED AERATED CONCRETE

Submitted by

TAYYAB ZAFAR

Has been accepted towards the partial fulfillment

of

the requirements

for award of degree of

Master of Science in Structural Engineering

Thesis Supervisor

_____

Dr. Muhammad Usman, PhD
Assistant Professor
Department of Structural Engineering
NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)
National University of Sciences and Technology (NUST)

Sep 2018, Islamabad Pakistan

ACKNOWLEDGEMENTS

All praise to Almighty Allah who gave the courage and power to the author for completing this research work.

I am thankful to my supervisor Dr. Muhammad Usman, for giving me time and support from initial to final level, made it possible for me to complete this work.

I am also cordially thankful to Dr. Rao Arsalan Khushnood, HoD Structural engineering department, NUST Institute of Civil Engineering (NICE). His able guidance and encouragement steered me to think beyond visible facts to bring more useful and applicable conclusions from the work in hand. His pleasant and friendly conduct facilitated me to discuss my view point on the subject in detail and addressed my queries to my entire satisfaction.

I must not forget the supporting role of my friends and especially Engr. Haseeb Taj, Engr. Usman Javed and Engr. Saeed Zafar student of Ms. Structural engineering at NICE, NUST and laboratory staff at NICE, for providing the technical assistance and cooperation during the reported research work.

Lastly, I want to thanks my parents and family members for supporting me in all phases of life.

ABSTRACT

Solid waste disposal of nonrecyclable waste glass is carried out through landfills. It is not an eco-friendly solution because glass is not biodegradable. Therefore there is a dire need for the utilization of such wastes. Since glass contains rich silica content, therefore construction industry has the potential to use it in replacement of fine aggregate, in ground form. This research deals with the Pozzolanic activity of finely ground waste glass on the mechanical, thermal and microstructural properties of AAC, when used as partial replacement with fine aggregates. In this study glass powder was replaced with fine aggregates at various levels upto 20%. After casting the specimens were steam cured at a temperature of 140 °C for 5 hours. The fresh tests conducted were air content and shrinkage while the hardened properties were investigated by performing compression, flexure, unit weight and water absorption tests. Acid attack was carried out to check the durability. Supplementary analysis was done to identify the Pozzolanic potential of finely ground waste glass by using SEM, EDX and TGA. Thermal conductivity test was done to check the thermal performance of autoclaved aerated concrete. The results indicated that 15% replacement exhibited positive response. 60% increase in the compressive strength and 45% increase in flexure strength was observed at GP15% than the control mix. Maximum unit weight was found to be at GP15% i.e. 1293kg/m^3. SEM/EDX showed the formation of hydration products and TGA testified the presence of Pozzolanic activity of glass powder with particle size less than 75 microns. Compared with control sample 30% increase in thermal conductivity was observed at GP15%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1. General

Concrete is a broadly used construction material for buildings, infrastructure, hydraulic dams, roads, tunnels, water retaining structures etc. Depletion of natural aggregate due to large production of concrete forced us to use by-products of industries as replacement of aggregate in concrete. To produce eco-friendly concrete by replacing traditional construction materials with various industrial by-products is currently adopted in construction industry. Chemical and physical composition of the waste glass, it is deemed as the most appropriate replacement for fine aggregate [1]. Furthermore, due to rapid urbanization and infrastructural development, huge quantity of glass is manufactured throughout the world. The process of recycling of glass is very expansive, hence most of the consumed glass is disposed as land-fill. In United States, in 12.8 million tons only 2.75 million tons out of waste glass was recycled and remaining was disposed as land-fill [2]. Glass is non-biodegradable materials, therefore its disposal as land-fill is not considered as environmental friendly. Therefore the usage of waste glass as partial replacement of fine aggregate and cement in construction industry is considered to be the most attractive option due to consumption of materials in large quantity, low quality requirements and extensive construction sites.

Autoclaved Aerated Concrete is defined as a special concrete which involves mixing of cement, lime, water, fine aggregate and blowing agents. It was first introduced in 1920's in Sweden as an alternative buildings material. It is considered as an eco-friendly building material with a very low environmental impact due to its production with greatly abundant components [3]. In comparison to conventional construction materials, autoclaved aerated concrete compromises lower thermal conductivity, lower density, lower shrinkage and lower environmental impact, it also provides ease of use in construction [4-6]. Moreover, low environmental impact is considered as one of the most important advantage of AAC. The entire life cycle of AAC from treating of starting materials to the disposal of AAC waste gives low environmental impact due to its high resource efficiency [7, 8]. Autoclaved aerated concrete is produced from the mixture of cement or blended cement, finely crushed quartz sand in which macroscopic voids are formed by the inclusion of pore forming agent

which is usually aluminium powder and steam curing is carried out under high temperature and pressure [9].

For sustainable construction, the waste materials utilization as replacement of fine aggregate and cement in concrete are increasing significantly in recent times [10]. Use of industrial by-products and wastes in autoclaved aerated concrete has been studied for numerous years [11-15]. These industrial by-products and waste include coal bottom ash, rice husk ash, fuel ash, bagasse ash, air-cooled slag and wheat straw ash. These materials have been used as partial replacement of quartz sand and cement in concrete. Furthermore, the use of waste glass as replacement of fine aggregate has been started many years ago. In past few studies were made to determine the effect of waste glass in concrete, when used as a substitute to fine aggregate and cement. Furthermore concrete containing waste glass was examined for fresh and hardened properties [16-18]. The aim of this research is to investigate the influence of partial replacement of quartz sand with waste glass powder on mechanical, thermal and microstructural properties of autoclaved aerated concrete.

1.2. Applications of Autoclaved Aerated Concrete

a. Autoclaved aerated concrete is used in the residential and commercial building construction.
b. Porous structure of autoclaved aerated concrete makes it superior fire resistant and insulating material, so it is preferably used in external walls. Therefore the improved thermal properties reduce the heating and cooling loads in the buildings.
c. In high rise buildings the lower density of autoclaved aerated concrete reduces the structural loads which ultimately reduces the required quantity of reinforcement and concrete for structural members.
d. Smooth finish of AAC makes it viable to be used for interior walls. A very thin coat of plaster is required for its finish.
e. AAC has the advantage that it can be cut at any shape with saw, and has no effect on strength and other properties due to cutting and can be used still for the same purpose.

1.3. Advantages of Autoclaved Aerated Concrete:

It has numerous advantages over conventional concrete:

a. Light weight

b. Lower Bulk Density
c. Higher Thermal resistivity
d. Lower Shrinkage
e. High Resistance against fire
f. Efficient in construction (Lesser construction time)
g. Energy efficient construction
h. Sound insulation

1.4. Research Methodology

The methodology of the study is given in detail as follows:

a. Characterization of Glass Powder, Lime and Sand.
b. Selection of Mix design
c. Study total early shrinkage response, density, water absorption and compressive and flexure strength for each formulation.
d. To have an insight into the response of glass powder's formulations in comparison to the control mix study microstructural properties.
e. Perform thermal conductivity analysis on control and glass powder's formulations
f. Study the response of all formulations against Acid attack

1.5. Research Objectives

Objectives of this study are as follow;

- To determine the influence of glass powder on the mechanical and thermal properties of AAC
- To determine the effect of glass powder on the Durability and Microstructural properties of AAC.

1.6. Scope of Research

Scope of the research is limited to study the influence of glass powder on Mechanical, Thermal and Microstructural properties of Autoclaved Aerated concrete using the aluminium powder as pore forming agent. Study of pre-foamed concrete is not covered in this research.

CHAPTER 2:LITERATURE REVIEW

2.1. Aerated Concrete

Aerated concrete is a light weight cellular concrete which may be consists of either cement based or lime based mortar. The cellular behavior is achieved by entrapping air bubbles in the mixture with the addition of an appropriate foaming agent. The aerated concrete can be both non autoclaved (foam concrete) and autoclaved [18].

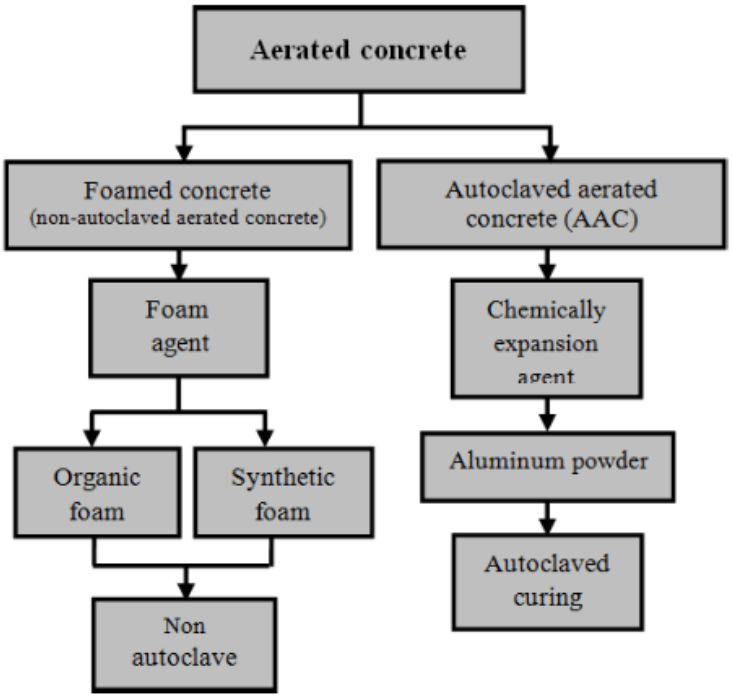

Figure 2. 1: Classification of Aerated Concrete [18]

2.1.1. Foamed Concrete

Foam concrete is produced by two methods, either by mixed foaming technique or Pre-foaming process. In pre-foaming process foam agent is mixed with water to form a stable foam and base mix cement paste (cement + water) or cement mortar (cement + sand + water) slurry is prepared separately and then stable foam and base mix slurry is mixed to form foamed concrete. In mixed foaming method, base mix of cement paste or cement mortar is prepared and then foaming agent is mixed into the mixture, foam is generated during mixing process and produce foamed concrete structure. The preformed foam is of two types: wet and dry foam. Wet foam is formed by sprinkling foaming agent solution on

finer mesh, it has bubble size from 2-5mm and its stability is comparatively less. Dry foam is formed when foaming liquid is forced through a series of closely packed restraints and compressed air is forced in the mixing compartment instantaneously. The bubble size is less than 1mm and comparatively dry foam is very stable [18].

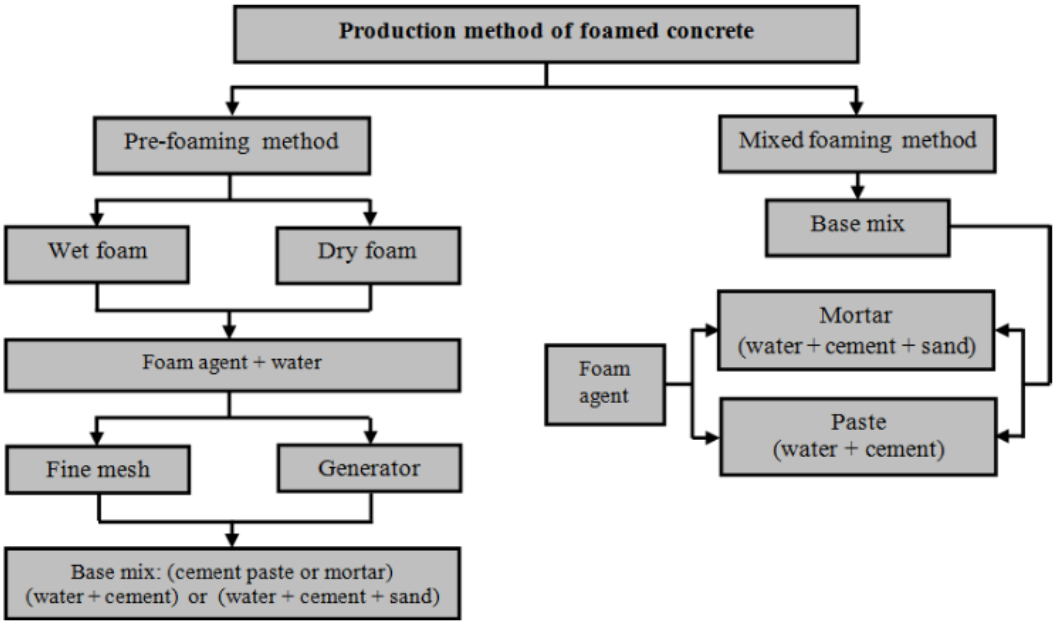

Figure 2. 2: Classification Process of Method for Foam Concrete [18]

2.1.2. Autoclaved Aerated Concrete (AAC)

Autoclaved aerated concrete is produced from finely graded raw materials. The main starting materials for the production of AAC are quartz sand or silica, cement, lime, gypsum or blended cements and also a foam forming agent which is usually aluminum powder. In the AAC mix higher percentages of silica sands are used than other aggregates. Quartz sand and silica can be obtained from granites or quarry rocks and both are mineral based aggregates. Fine aggregates (silica) can be replaced with fly ash, slag or mine tailings. Mixture is prepared by adding quartz sand, silica, lime and cement. When water is added to the mix hydration reaction starts which forms bond between cement paste and fine aggregates. After preparing slurry, the pore forming agent (which is normally aluminum powder) is added to the mix. The portlandite which is product of hydration reaction when reacts with aluminum powder, hydrogen gas bubbles are formed which rises the volume of the paste and contributes to the high porosity. Being lighter the hydrogen gas bubbles up to escape from the mixture and the empty spaces are occupied by the denser gas which is air.

The volume increase depends on the amount of aluminum powder added to the mix to react with portlandite (Ca (OH) $_2$) [18]. The reaction is shown in the following equations,[19, 20]

$$2Al+3Ca(OH)_2+6H2O \longrightarrow 3CaO.Al2O3.6H2O+3H2 \quad [20]$$

Aluminum powder + Hydrated Lime ⟶ Tricalcium Hydrate + Hydrogen [21]

The lower porosity induced will cause denser matrix and consequently higher strength material and vice versa. Autoclave is a pressure vessel in which accelerated curing is carried out. The working principle of autoclave is similar to the pressure cooker. Autoclaving is a process in which concrete is cured under high temperature 180c and pressure 15psi for certain time duration (8-16) hours. The drying shrinkage is reduced significantly for aerated concrete when curing is carried out in autoclave and it is indispensable to make aerated concrete product within adequate level of strength and shrinkage [18].

Aluminum powder has been proved as the best solution for the production of AAC around the globe. Aluminum powder is usually added about 0.2% to 0.5% by dry weight of binder content. In AAC industry Aluminum powder is often manufactured from scrap foils and it occurs in the form of flaky shaped particles. Aluminum powder with particle size less than 50 microns can form dust clouds easily during pouring or vibration, which are highly flammable. The use of aluminum powder with grain size less than 100 or 50 microns produces AAC whose mechanical properties are better [18].

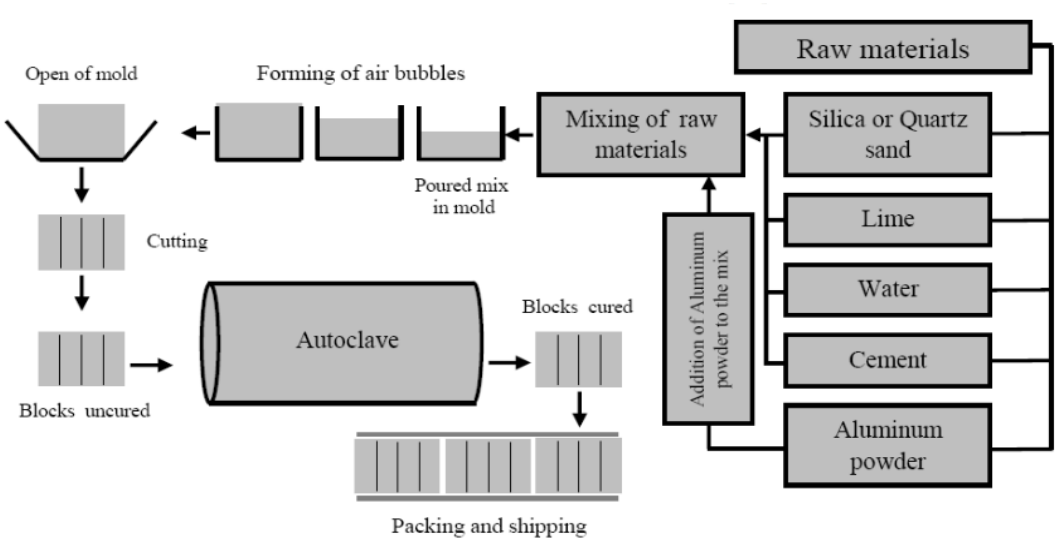

Figure 2. 3: AAC Production Phases [18]

2.2. Classification of Autoclaved Aerated Concrete

Aerated concrete is a light weight cellular concrete which may be consists of cement mortar, lime mortar or mixture of both. The cellular behavior is achieved by entrapping air bubbles in the mix with addition of an appropriate foam forming material. The properties of this concrete depends on the curing method. There are two methods of curing autoclaved curing and non-autoclaved curing. Based on all these factors aerated concrete can be classified as following:

2.2.1. Based on Pore Formation Method

2.2.1.1. Air Entraining Method

Generally during the liquid stage of aerated concrete some air entraining chemicals are added by some percentage of binder. Hydrogen peroxide, oxygen, acetylene and aluminum powder can be used as aerated agent. Due to better efficiency of aluminum powder it is most commonly used aerated agent. Aluminum powder in presence of water reacts with lime (calcium hydroxide) resulting the formation of hydrogen gas and tri-calcium hydrate. The hydrogen gas then evolved out of matrix and replaced by the air bubbles as hydrogen is lighter gas then air [5].

2.2.1.2. Foaming Method

Foam concrete can be achieved by two methods either by mixed foaming or pre foaming method. Previous literature reported this method as economical and controllable method comparatively [21, 22]. Foaming agent is further classified into two categories either synthetic based or protein based. The most commonly used foaming agents are resins soap, glue resins, detergents and hydrolyzed proteins. The air entraining and foaming method can also be used in combination to achieve aerated concrete.

2.2.2. Based on Type of Binder

Aerated concrete can be consists of cement mortar, lime mortar or mixture of both. Use of some pozzolanic raw materials are also reported in literature such as coal bottom ash, Rice husk ash and blast furnace slag etc. [13, 23, 24].

2.2.3. Based on Method of Curing

Aerated concrete can be categorized as Non Autoclaved and Autoclaved concrete. The key properties of aerated concrete including compressive strength, absorption and drying shrinkage are dependent on the duration and method of curing [5].

2.3. Previous Studies on Autoclaved Aerated Concrete

Previously several research studies have been carried out on AAC. In these studies different properties of AAC were put under consideration by adding some siliceous materials as partial replacement of cement or sand.

H. Kurama et al. in 2007 worked on partial replacement of coal bottom ash with sand in AAC and examined the different properties of AAC including physical, mechanical and chemical properties. The replacement percentage was kept from 0 to 100%. Aluminum powder was used for the liberation of hydrogen gas to produce aeration in concrete. The autoclaved curing of specimen was done for 8 and 18 hours and examination of product was done against these two curing periods. XRF, XRD, FESEM, thermal conductivity test and ultra sound pulse velocity test techniques were used to study different features of coal bottom ash in autoclaved aerated concrete [13].

The results showed that 50% replacement of BA is the optimum value for all the tests conducted in this work. The density of the resultant concrete decreased with the increment of bottom ash because of porous structure of BA and loss in unit weight for 8h curing time was more than 18h curing time. For 100% replacement of BA, loss in unit weight was almost equal. Thermal conductivity decreased with increase in replacement value of BA.

Mechanical tests result showed that compressive strength was highest for 50% replacement of BA and then reduced with further addition of BA. For 18h curing time the results were impressive. Due to the improved microstructure because of better pozzolanic activity the compressive strength was also improved. No significant values were obtained for flexure test because of very low curing time for the test. Microstructural analysis revealed that up to 25% addition of BA, the C-S-H is gathered by quartz particle. Because of tobermorite

formation which owe to increase in pozzolanic activity and cause increase in strength with reference to traditional AAC [13].

Kittipong Kunchariyakun et al., 2014 investigated the mechanical, physical and microstructural properties of AAC by incorporation of rice husk ash at different replacement ratios with fine aggregates at constant temperature of 180 ⁰ C and autoclaving time of 8 hours and 18 hours. After experimental study he reported the reduction in compressive strength and unit weight with the addition of rice husk ash. In case of microstructure the tobermorite transformation was affected due to presence of highly reactive silica in RHA. When autoclaving was done for 8 hours the tobermorite crystals lath and plate like morphology were detected in mixes. At increased replacement ratios glass like silica rich CSH was replaced about 50% with RHA. After increasing autoclaving time there was no such improvement noted on these properties. The final conclusion of this study was that incorporation of RHA has ability to reduce the autoclaving temperature or autoclaving time required for the production of AAC [23].

Zühtü Onur Pehlivanlı et al. in 2016 worked on the autoclaved aerated concrete using different fiber reinforcements. He explored the mechanical and thermal properties of AAC. He added carbon, polypropylene, basalt, and glass fibers in AAC of class G3/05 and G4/06 which were used as elements of wall in building.
By performing this experimental study, he concluded that the thermal conductivity was highest when basalt fibers were induced in AAC. Also the samples containing carbon fibers give optimum value of flexure and compressive strength [25].

Narayanan, Ramamurthy in 2009 done a detailed investigation on microstructural characteristics of aerated concrete. SEM and powder XRD studies were done on moist cured (up to 180 days) and AAC (up to 10 hr.) using sand and fly ash as filler. Specimens were composed of cement and sand or fly ash and fix amount of lime was used for aeration purpose.

The compressive strength result revealed that strength of AAC was more than that of moist cured concrete and also for sand, the compressive strength was more than fly ash. The

reason for such results was attributed to different microstructural behavior of AAC and moist cured. Similar is the case with sand and fly ash [26].

For moist cured concrete, according to author, the hydration products are continue throughout the matrix. In case of fly ash, the particles of fly ash become nucleation site for cement, hence result in incomplete hydration process leading to lower strength. Similarly for sand, the microstructure behavior does not change with time but using fly ash, the structure is unstable. In first stage fibrous gel is formed which then transformed to needle like prismatic structure. Pore refinement of fly ash is good after complete hydration because of its pozzolanic action.

For AAC, the microstructure behavior is completely different than moist cured concrete when sand was used which is because of formation of well-defined calcium silicate hydrate gel and calcium hydroxide. In case of fly ash, poor crystallinity leads to lower strength. The ITZ's are also present in cellular concrete as in normal concrete but here it exists in the voids-paste interface [26].

Vishal kansagra, in his project report "A brief report on Autoclaved Aerated Concrete" discussed about the general features and the history of Autoclaved Aerated concrete. In this study the different features of AAC were studied and it was concluded that AAC blocks are about 50% lighter than clay bricks of equivalent size also it is easy to use, versatile in nature, long life, eco-friendly, good thermal insulation, higher fire resistance , good sound insulator, and has ability of weather resistance [27].

2.4. Previous Studies on Glass Powder

Crushed glass as partial fine aggregate replacement has been reported in literature since several decades back [28], therefore research on pozzolanic glass powder in concrete is recent advent [29, 30]. Pozzolanic nature of waste glass was explored in view of high economic costs of recycling of waste glass as well as the environmental issues related to disposal of waste glass. As the chemical composition of glass does not vary significantly despite their origins, potentially strong pozzolanic properties of waste glass materials found its economical applications.

The recycled glass powder is occasionally used as supplementary cementitious materials but recently it is also used as fine aggregate based filler material [31, 32]. Fineness of glass powder imparts pozzolanic activity while coarser particles contribute toward poor ITZ and cause alkali-silica reaction (ASR) which is deleterious for concrete.

Huge surface area of finely ground glass with high amorphous silica content fulfills the chemical requirement of ASTM C618 [33] for pozzolanic material. The rich silica content, fine particles and amorphous structure of glass powder makes it suitable to be used as a secondary raw material (SRM) and, so, it can be used to substitute a percentage of the cement in concrete. Large amount of al-kalies present in waste glass makes the concrete more vulnerable to the alkali- silica- reaction (ASR), when glass is used as aggregate, especially if its particle size is small, will itself release enough alkalis to induce ASR [34]. Oxides of sodium (Na20) and potassium (K20) in glass could potentially be released in the form of sodium and potassium ions, thus can increase the pH of cement paste. GP has a higher amount of alkalis than other pozzolans, such as FA and SF, which do not undergo ASR, so glass might prove to be a weaker pozzolana or even induce ASR in reactive aggregates.

This aspect of Glass has been recognized and is the subject of intense research as reported in previous published literature [35]. However, finely ground glass powder has pozzolanic potential thus inhibit the ASR [36]. Further efforts have also been undertaken to characterize and utilization of waste glass as cement or aggregate replacement with some positive results [37, 38].

Reactivity of waste glass powder depends on the physical and chemical properties of glass such as size, shape, pores and solid phases [37, 39]. For example, both sodium silicate glass and soda-lime glass behave differently in concrete, in which former one cause alkali release and mortar expansion, whereas soda-lime glasses is alkali deficient and do not cause expansion by chemical deleterious effect [35, 39].

Generally, Pyrex glass containing boron was found more reactive than soda lime silica glass [39]. The reactivity of waste glass powder as fine aggregate in concrete is influenced by its particle size and alkali content in cement [37, 39, 40].

Shao et aI [41] reports the strength development and pozzolanic activity of finely ground WGP, SF and Fly Ash at 30% replacement of cement. The glass powder particle size used were 38, 75 and 150 µm. Authors reports that the mix with 30% silica fume achieved improved results than the reference mix at 28 days; conversely, at 90 days age, the concrete with the 38 µm glass powder replacing cement produced concrete that is 8 % higher in strength in comparison to the control. The fiber glass incorporated concrete produced higher compressive strength than that of coarser glass cullets due to reactivity of finely grounded glass powder.

According to ASTM C 618 [33], 75% of strength activity index is required to be pozzolana to impart appreciable beneficial to concrete. The 75 and 38 µm waste glass powder satisfied this requirement and their corresponding mixes achieved results similar to fly ash.
Shayan and Xu [42] investigated the use of GP with particle size finer than 10 µm to replace the cement in RM on various levels. The 28 days compressive strength was lower for glass powder mixes than the reference mix. However, the 90 day strength of the concrete was higher or approximately the same as that of the reference for all the mixes with waste glass powder. This is endorsed to the pozzolanic reactivity of the waste glass powder, although its rate of hydration is slower than the OPC [42].

The work of Schwarz et al [34] has suggested that it is optimal to replace 10% of cement with WGP when 72% of the particles were smaller than 45 µm. However, the optimum replacement of cement with FA was 20%. The concrete paste having 10% glass replacement with cement gave better response than the concrete modified with FA at 28 days, in terms of strength, however, at 90 days, the fly ash mix had higher strength. This was endorsed to the greater pozzolanic activity of fly ash.

Sylvia Nicole Mihaljevic [43] has studied the effect of waste glass powder on the performance of concrete masonry blocks and reports that the replacement upto 10% of cement with waste glass powder has no contrary effects on the performance of concrete blocks and the compressive strength and ASR of waste glass powder and control mix were comparable (a variation of 11%). However, for upto 25% replacement, the waste glass powder mix shows more expansion than the control mix even upto 28 days. Although

this expansion was within acceptable limits prescribed in ASTM C 1260 (2007) [44], further testing and investigation is recommended to confirm these findings.

Paweł Walczak worked on “Waste glass utilization in AAC”. This experimental study was carried out to design autoclaved aerated concrete for mass housing project with substitution of different types of glass wastes in order to contribute in the controlling of environment from pollution. Sub grain packaging glass cullet, CRT panel glass waste and calsi glass were the different types of glass wastes used as fine aggregate in AAC production. As AAC was initially investigated as an insulation material, as it is light weight, material which has the potential for the utilization of waste materials on large scale. Taking the above benefits in consideration different types of glass wastes were substituted in autoclaved aerated concrete and different tests were performed to investigate its physical, chemical and mechanical properties [45].

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1. Materials

All the materials used in this research were obtained locally and stored in air tight containers to prevent any possible ingress of moisture. Aggregates were taken in as available condition and were cleaned to remove impurities that might affect the properties when used in AAC. Other details regarding each and every material used during this research study are provided as under;

3.1.1. Cement

OPC of Grade 53 Type-1 by Pakistan Standards PS-232-2008, manufactured by 'Bestway cement limited' conforming to ASTM C150-04 and EN-196 was used. The (XRF) analysis was done to find the chemical composition of cement. Particle size distribution and Specific surface area was determined using laser particle size analyzer (BT-9300ST) as shown in Table 3.1;

Table 3. 1: Chemical composition and Physical Analysis of OPC

SiO_2	19.17
TiO_2	0.28
Al_2O_3	4.96
Fe_2O_3	3.21
MnO	0.04
MgO	2.23
CaO	65.11
Na_2O	0.57
K_2O	0.51
P_2O_5	0.77
LOI	3.85
BET (m^2/g)	1.1
Particle Size, (D_{50}), microns	16.2

3.1.2. Lime Powder

Quick Lime powder was manufactured by grinding Lumps in locally available china made grinding plant. The grinding process was observed very keenly to avoid inclusion of any impurities and to have the particles of smallest possible size. LP obtained after grinding was passed through sieve having aperture of 45 micron (BS-410 #350/ ASTM E-11 #325). After manufacturing. D_{50} of LP was found to be around 1.89 micron.

LP is reactive in nature and due to its rough surface, it offers nucleation sites for growth of hydration products [18]. Rough surface texture of LP also offers resistance against the

flow of AAC. Also from XRD it has been found that it is of crystalline nature. SEM images and XRD of LP showing its rough surface texture can be seen in figure 3.3.

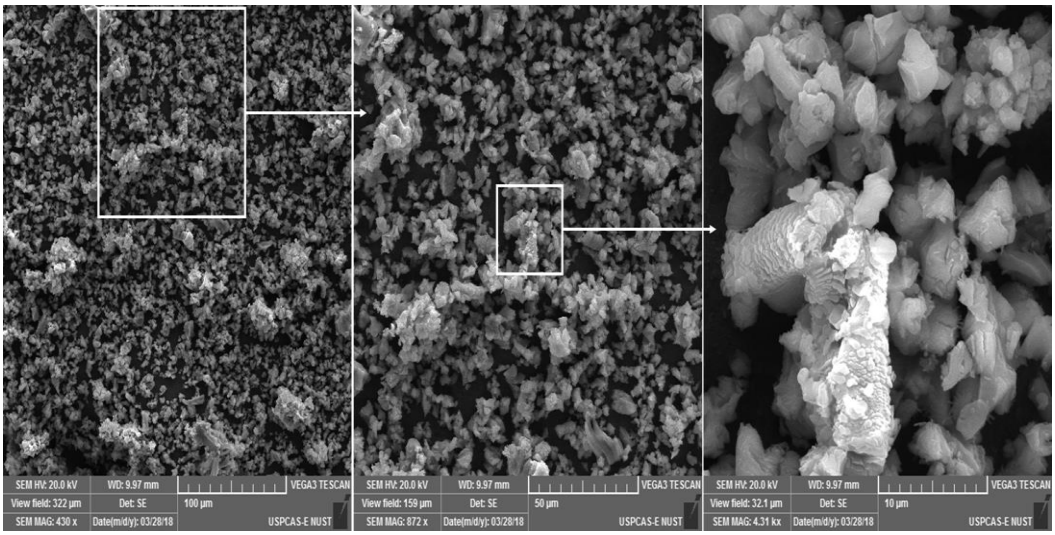

Figure 3. 1: SEM Images of Lime Powder at different magnifications

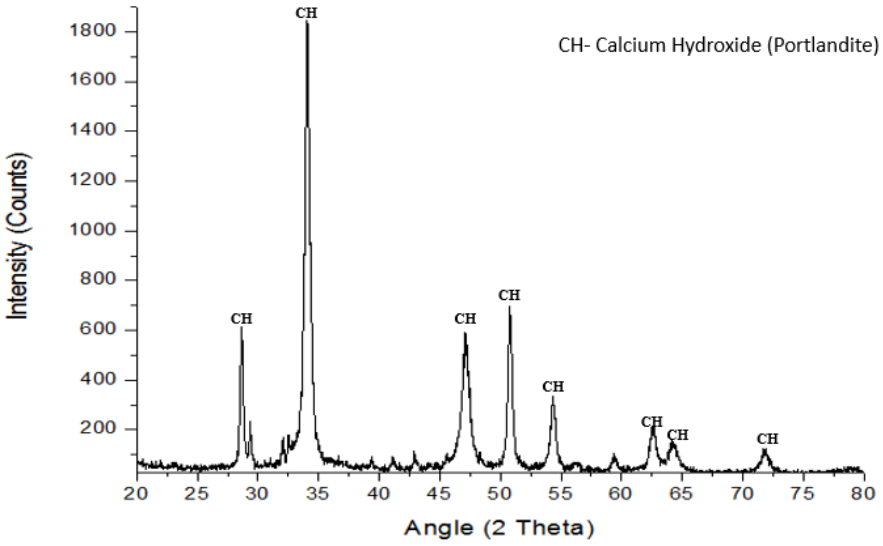

Figure 3. 2: XRD pattern of Lime Powder

3.1.3. Glass Powder

Glass Powder used in this study was obtained from PCSIR lab Peshawar. After grinding it was passed from sieve #200. After manufacturing. D_{50} of GP was found to be around 69.8 micron. GP is reactive in nature and it offers Pozzolanic activity when used in finely ground form. The particle size less than 100 microns offers sufficient Pozzolanic activity. The finer the particles of glass powder, higher will be the Pozzolanic extent. Also from XRD its amorphous nature has been revealed. SEM images of GP showing its Granular and Irregular surface texture.

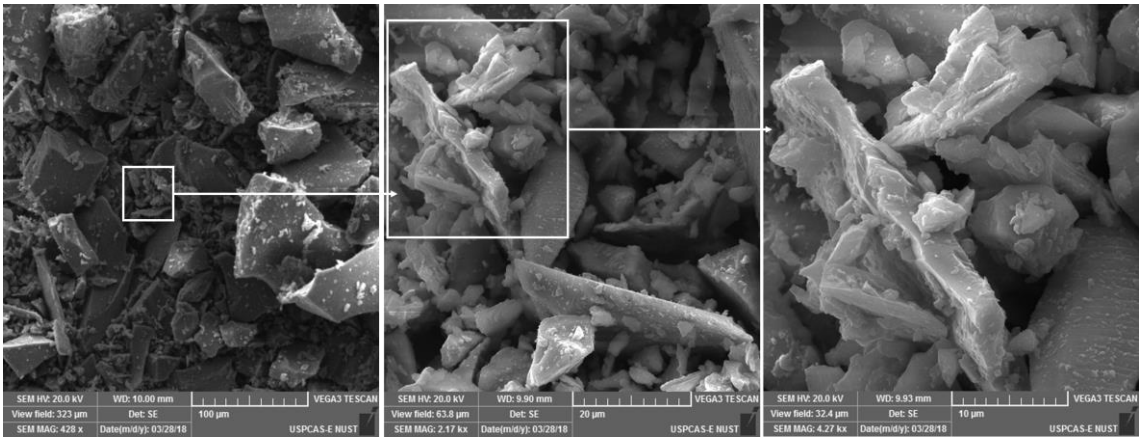

Figure 3. 3: SEM Images of Glass Powder at different magnifications

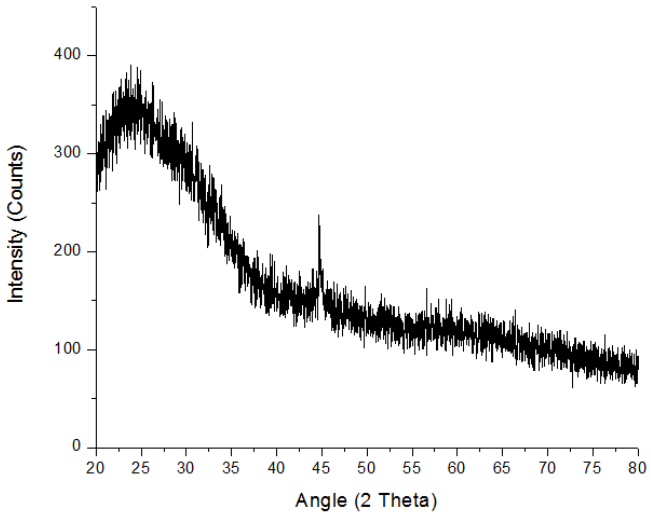

Figure 3. 4: XRD pattern of Glass Powder

3.1.4. Fine Aggregate

Sand used for this research work was obtained from the fine sand deposits of Chenab river. It was properly cleaned before use to remove any organic matters. Fineness Modulus (FM) of the sand was found to be 1.23, determined as per ASTM C-136. FM of Chenab river sand is observed to be lower than the specified range of 2.3-3.2, as given in ASTM C-33 which results in increased porosity in the mixture. Sieve analysis results of fine aggregate used can be seen in Figure 3.4.

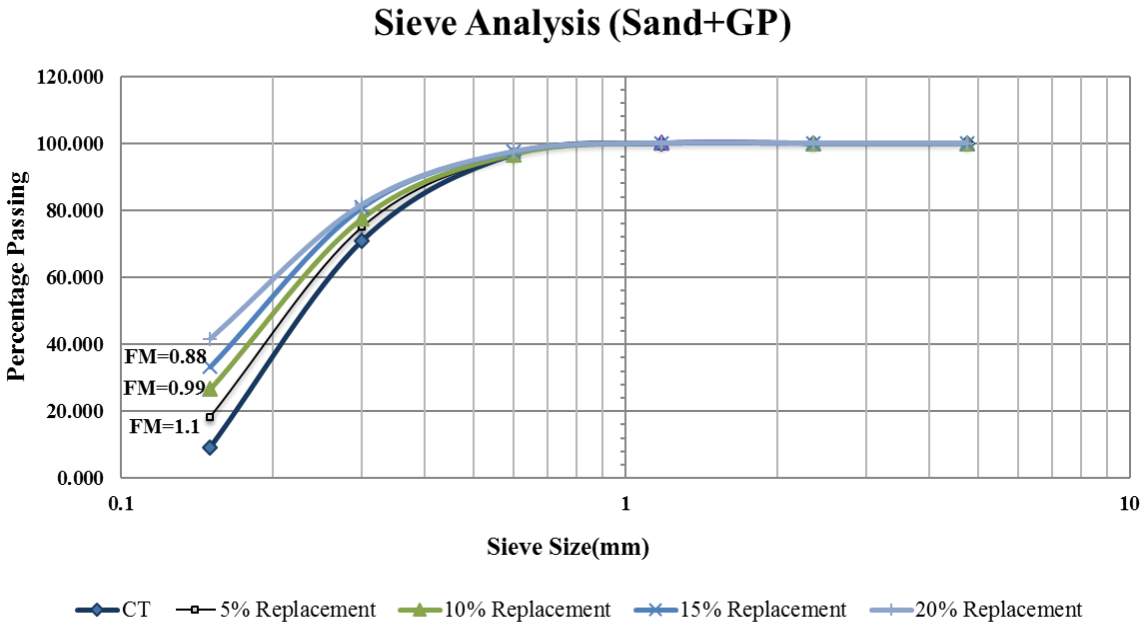

Figure 3. 5: Particle Size Distribution of sand and glass powder composite

3.1.5. Pore Forming Agent

Aluminium powder was used as a blowing agent in the formation of Autoclaved aerated concrete. Uni-Chem Aluminium powder was used in this study. It was 99.99% pure. Its average particle size was 10 microns. A chemical reaction took place between Aluminium powder and $Ca(OH)_2$. In the result of this reaction hydrogen gas bubbles were formed in the mortar in fresh state. It was added about 0.5% by dry weight of binder content.

3.2. Experimental Program

The research study was carried out in a very organized manner. All the experimental procedures for each and every testing and investigation are described below: the flow chart showing the experimental program is as follows;

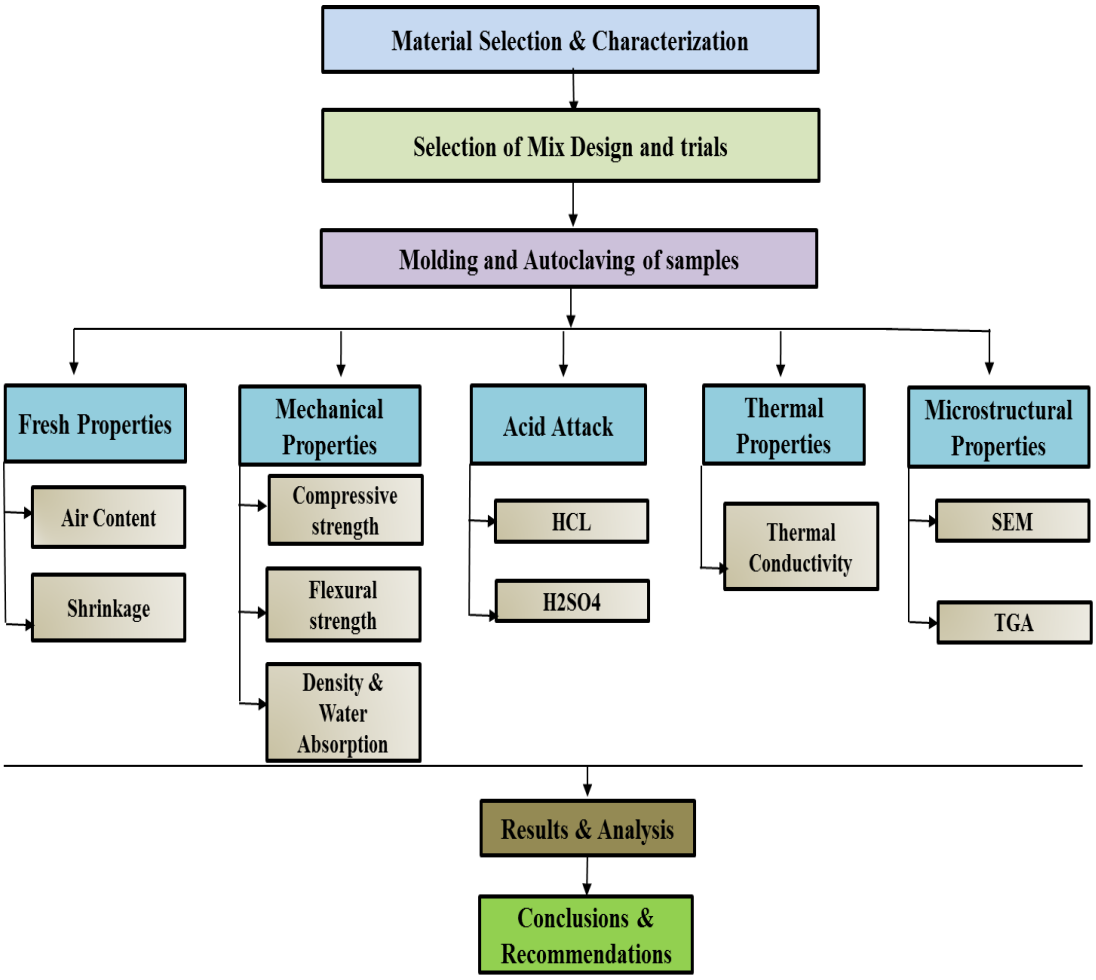

Figure 3. 6: Flow Chart of Experimental Program

3.2.1. Mixing Regime and AAC Formulations

The mix design of all mixes is shown in Table. All mixes contain 45% of cement content and 5% of quick lime and variable concentration of glass powder with the replacement of sand, which ranges from 0 to 20% (0, 5, 10, 15 & 20%). Aluminum powder was incorporated as foaming agent which is usually added 0.5% by mass of binder which are Portland cement and lime. The water/ binder ratio was 0.65 which was constant for all mixes.

Mixing was done in Hobart mixer, first dry mixing of constituents was done for 1 minute and then after adding water again mixing was done for 1.5 minutes. The mixed matrix was poured into 5 x 5 x 5 cm^3 cube moulds. After moulding process preheating of the sample was done in oven for 3 hours at a constant temperature of 40 ^{0}C to attain the desired volume stability and desired setting. Autoclaving of samples was done at constant temperature of 140 ^{0}C for 5 hours in autoclave chamber at high steam pressure of 11 Psi. For compressive strength test samples were dried in oven for 24 hours at constant temperature of 40 ^{0}C so that moisture content remains 5% to 15% in samples as coded in ASTM C1368. The other test samples were oven dried at 105 ^{0} C for 24 hours.

Table 3. 2: Mix Design of AAC Formulations

Samples	OPC (wt. %)	Cao (wt. %)	Sand (wt. %)	Glass Powder (wt. %)	Al.powder	W/B ratio
CT	45	5	50	-	0.5	0.65
GP 5%	45	5	45	5	0.5	0.65
GP 10%	45	5	40	10	0.5	0.65
GP 15%	45	5	35	15	0.5	0.65
GP 20%	45	5	30	20	0.5	0.65

3.2.2. Air Content of Fresh AAC

Luftgheltsprufer apparatus was used to find air content of fresh formulations as shown in Fig. 3.7. ASTM C-231 standard guidelines were followed while performing these tests. It is equipped with 1 liter capacity.

Figure 3. 7: Luftgheltsprufer-Air Content Testing apparatus

3.2.3. Strength Tests

For compressive strength test, the dimensions of the specimens were 5x5x5 cm^3. While for flexure strength test, prism of 4x4x16 cm^3 were cast. Three specimens were tested according to BS EN standards for each formulation and average results were reported. For determining compressive and flexure strength of each formulation at 5 hour of accelerated curing, specimens were tested in the direction of their rise in compression testing machine according to ASTM C1368 standards as shown in Fig.3.8.

Figure 3. 8: Compression testing machine

3.2.4. Water Absorption Test

Water absorption capacities of all the AAC mixes were determined according to ASTM C642-97. The test was performed on the 5 cm x 5 cm x 5cm cubes. After 5 hours of steam curing, cubes were taken out of water and oven dried at of 100±5 °C for 24 hours. Then cubes were taken out of the oven and weighed in dry conditions. Then cubes were kept in water for 24 hours and weighed in SSD conditions. The Difference of two weights for each cube gave the moisture content absorbed by the respective formulation.

3.2.5. Early Total Shrinkage

It is the total shrinkage of any cementitious system which is important as it affects volume stability. To assess the volume stability of formulations with and without glass powder content total autogenous shrinkage data was logged for first 24 hours for all OPC based formulations using modified version of shrinkage channel apparatus with dimensions 4x6x25 cm^3 and a sensitivity of 0.31 microns as shown in Fig. 3.9. Linear shrinkage for each formulation was determined using linear change protocols. The test specimens were covered with a polythene sheet to minimize moisture exchange with environment.

Figure 3. 9: Shrinkage channel apparatus

3.2.6. Scanning Electron Microscopy

To investigate the particle size, shape and morphology of Lime Powder and Glass Powder and also to study the hydration products, microstructure and ITZ of AAC formulations, scanning electron microscopy was carried. Broken pieces of AAC mixes were collected and oven dried at 100±5 °C for 24 h to stop the hydration process and make the samples free from moisture. Then samples were broken into required size and stuck with carbon tape on studs to obtain clear and more perceivable images. Then gold coating was done using sputter coater. SEM analysis was performed using model "TESCAN VEGA3".

3.2.7. Energy Dispersive X-Ray (EDX) Analysis

To verify the formation of tobermorite crystals in AAC formulations containing dosage of glass powder EDX spot analysis were performed on each of the three specimens considered for SEM using the model "TESCAN VEGA3" Scanning electron microscope equipment to study the chemical composition.

3.2.8. Resistance to Acid Attack

For determining the resistance to acid attack, three cubes (5cm x 5cm x 5cm) samples of each formulation were casted. After pouring the slurry of mixes in to the moulds, preheating was carried out for 3 hours at a temperature of 40 °C. Then steam curing was

carried out for 5 hours at a temperature of 140 °C. After curing samples were taken out and dried in oven for 24 hours at a temperature of 100±5 °C and dry weights were recorded. Now the samples were immersed in 5% solution of hydrochloric and sulfuric acids for 28 days. After 28 days samples were again dried in oven for 24 hours. Percentage weight loss was determined from these recorded weights. This test was carried out to check the durability of AAC mixes.

3.2.9. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis of AAC mixes was done to explore the possible Pozzolanic potential of glass powder. Thermogravimetric analysis was performed on CT, GP15 and GP20 mixes. Qualitative analysis was carried out on specimens of AAC mixes after steam curing of 5 hours at a temperature of 140 °C. Samples were kept in controlled furnace and Nitrogen gas was used as atmosphere at a rate of 50 ml/min in the furnace. Starting temperature was kept 28 °C for 2 minutes and then temperature was increased upto 900 °C at a controlled rate of 10 °C/min. The weight loss was logged corresponding to the temperature of samples during the disclosure time.

3.2.10. Thermal Conductivity

To investigate the durability and insulation properties of three specimens used in SEM and EDX analysis, Thermal conductivity tests were performed on AAC samples with surface area 50mm x 50mm at NED University of Engineering and Technology Karachi.

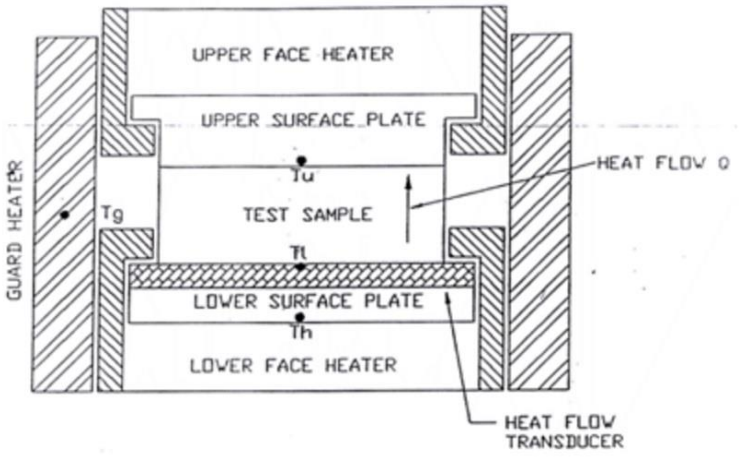

Figure 3. 10: Guarded heat flow meter apparatus [ASTM 1530-11]

Thermal conductivity describes the insulation properties whereas electrical resistivity is a measure to quantify the ability to resist corrosion or durability of cementitious systems. Thermal conductivity tests were performed following ASTM E1530-11 Standards, using guarded heat flow meter apparatus as shown in Figure 3.10.

CHAPTER 4:RESULTS AND DISCUSSION

4.1 Air Content of Fresh AAC

Air content of all mixes was determined with Luftgheltsprufer apparatus which is equipped with 1 Liter capacity. The results of air content are presented in Fig. 4.1;

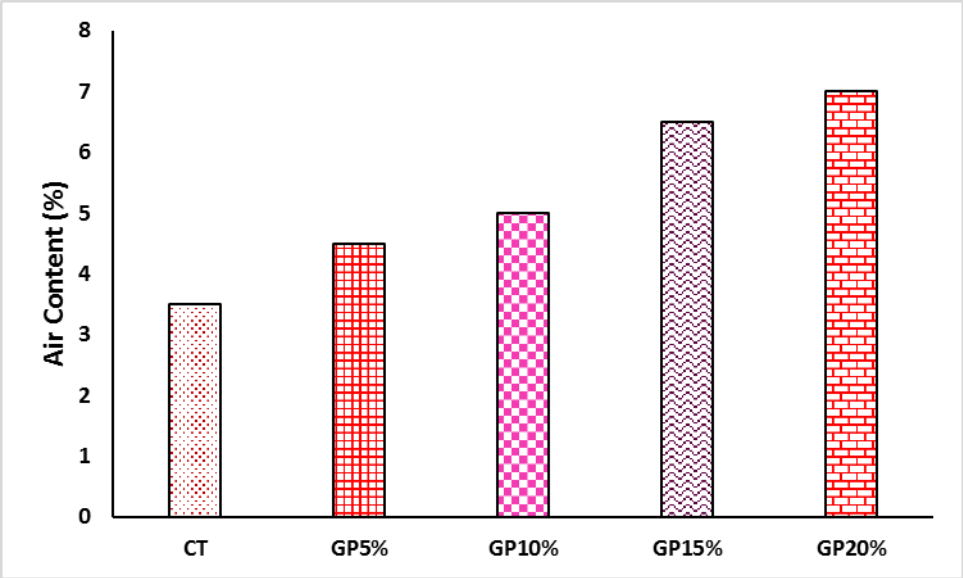

Figure 4. 1: Air content of AAC mixes

As the percentage replacement of glass powder is increased, the air content in the fresh paste also increased. It is due to the more finesse of the fine aggregates. Because it increases the porosity with in the mix.

4.2. Compressive Strength of AAC

Compressive strengths and relationship between compressive strength and dry densities of AAC formulations obtained are illustrated in Fig. 4.2 and Fig. 4.3 respectively. Fig. 4.2 shows that the AAC with 15% of glass powder content achieves maximum compressive strength (10.1 MPa) as compared to the control mix. This maximum strength of GP15% may be related indirectly to the density of respective AAC mix., shown in Fig. 4.3 as the AAC mix unit weight increases the compressive strength increases and whereas with the decrease in unit weight the compressive strength of AAC mix decreases respectively.

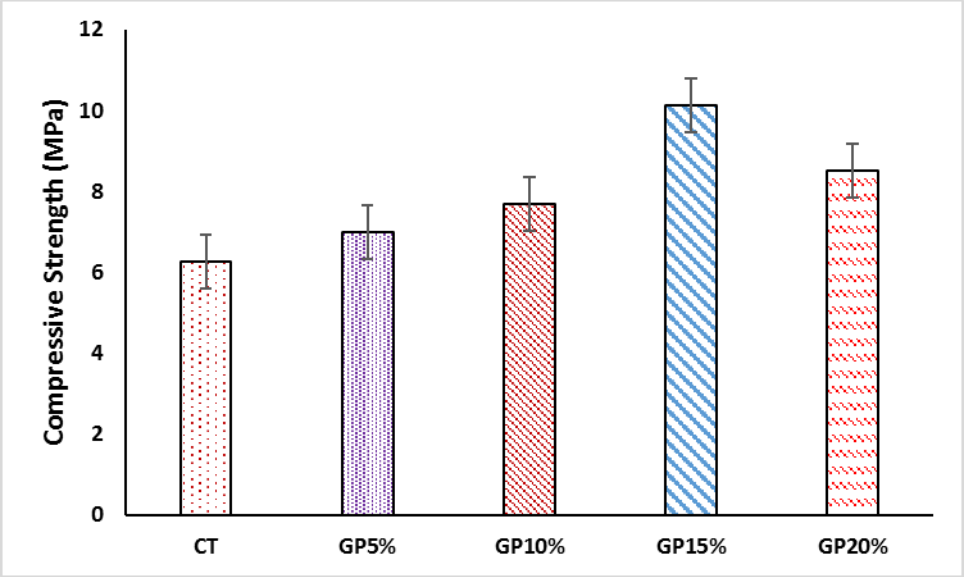

Figure 4. 2: Compressive strength of AAC mixes

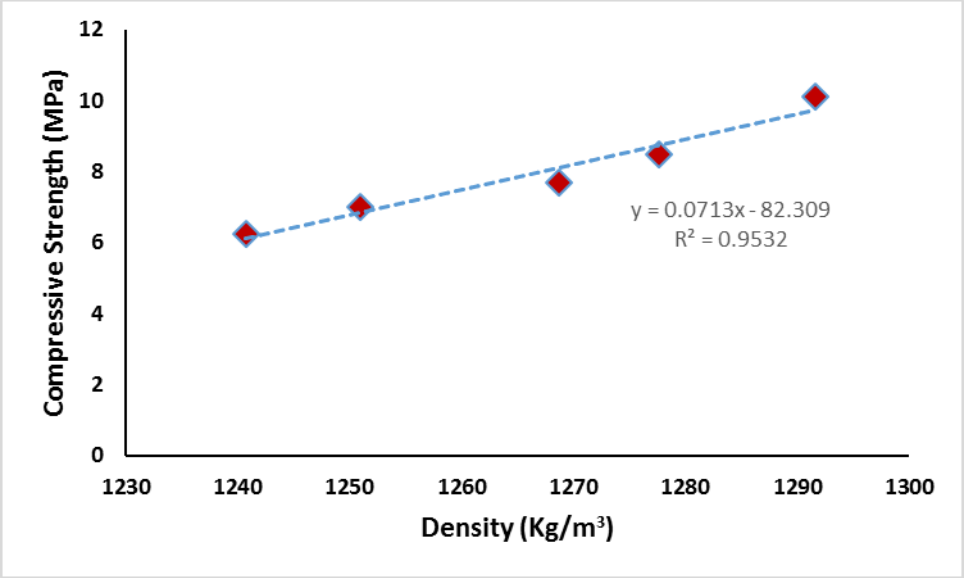

Figure 4. 3: Relationship between flexure strength and density of AAC

4.3. Flexure Strength of AAC

Flexure strength and relationship between flexure strength and dry densities of AAC formulations obtained are shown in Fig. 4.4 and Fig. 4.5 respectively.

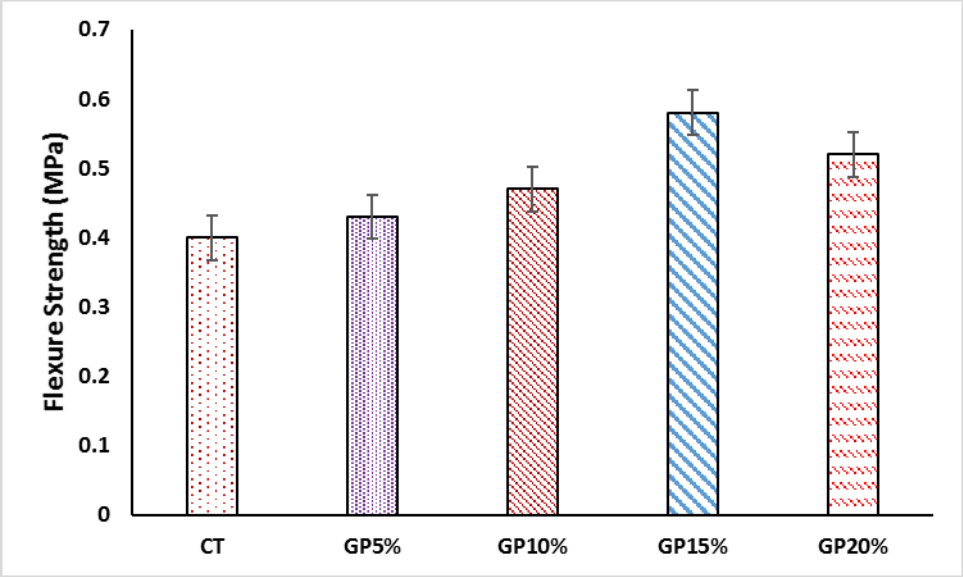

Figure 4. 4: Flexure strength of AAC mixes

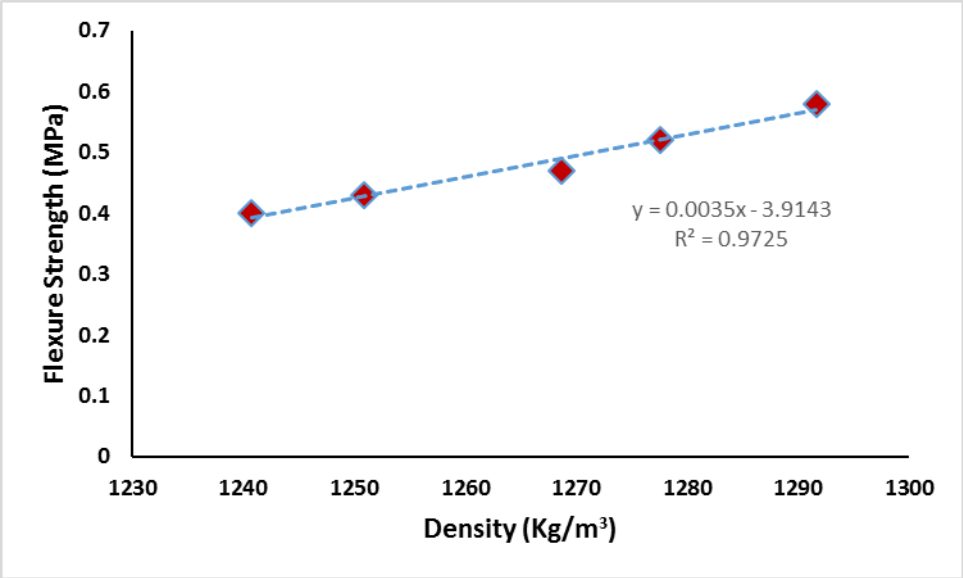

Figure 4. 5: Relationship between flexure strength and density of AAC

Fig. 4.4 shows that the AAC with 15% of glass powder content attains maximum flexure strength (0.58 MPa) than the reference mix (0.4 Mpa). This maximum strength values attained for GP15% mix may be related indirectly to the density of respective AAC mix. [35], shown in Fig. 4.4 as the AAC mix density increases the flexure strength increases and whereas with the decrease in density the flexure strength of AAC mix decreases respectively.

4.4. Unit Weight and Water Absorption of AAC

The dry densities of AAC samples cured for 5h are illustrated in figure 4.6. The results indicate that dry densities follow the similar trend as that of compressive strength and flexure strength. The unit weight of AAC samples increased as the percentage replacement of glass powder is increased. The minimum and maximum values of dry density were observed for control and GP15% mixes and were equal to 1240 and 1293 Kg/m^3 respectively. This increase in the unit weights of AAC samples may be related to the physical and chemical contributions. Physical contribution is due to the higher specific gravity of glass powder (2.61) as compared to the quartz sand. Chemical contribution is due to the Pozzolanic activity of the glass powder which replaced the lower unit weight CH crystals and CSH gel with the higher unit weight tobermorite crystals. The relationship between density and water absorption is also shown in figure 4.6. Water absorption capacity or permeability is significantly reduced for AAC containing glass powder as compared to control mix. The reduction in water absorption is related to the dense microstructure of AAC with glass powder replacement. It is due to the close packing of hydration products which is due to the outgrowth of tobermorite crystals bridging the pores as visible in SEM micrographs in Fig. 4.9.

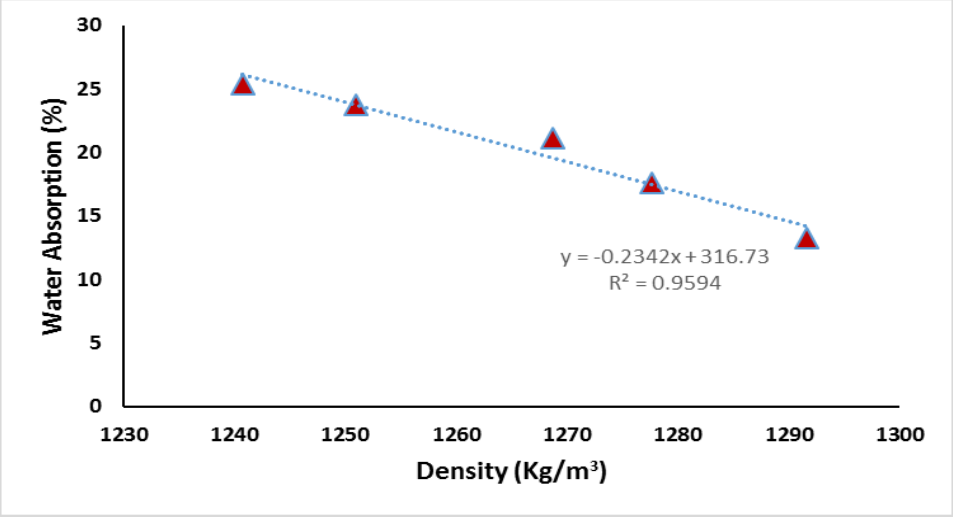

Figure 4. 6: Relationship between the water absorption and density

4.5. Early Total Shrinkage Measurement of AAC

Early total shrinkage measurements were recorded for 24hrs using modified shrinkage channel apparatus in structure lab as shown in the Fig.14:

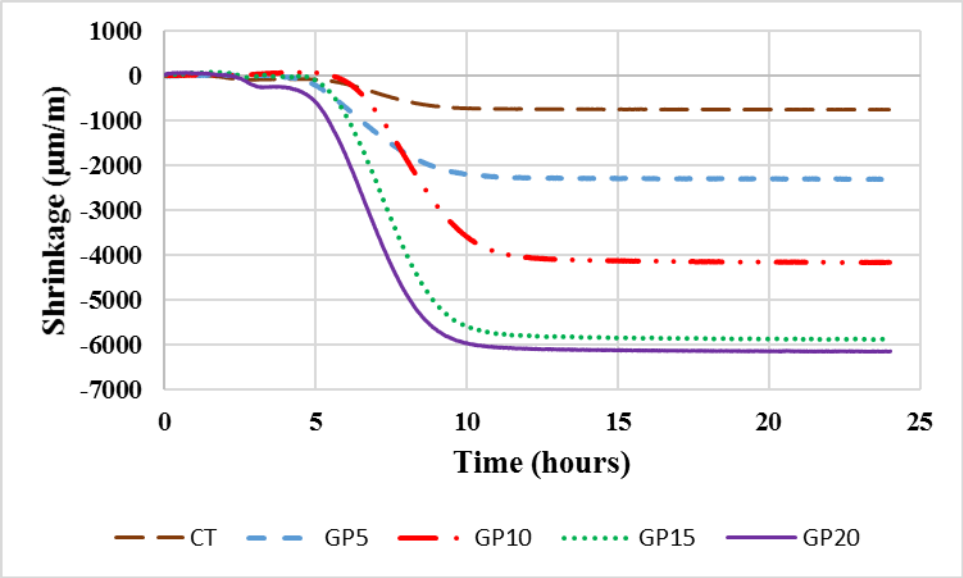

Figure 4. 7: Shrinkage Response of AAC mixes

Fig. 4.7, clearly portrays the shrinkage response of all the formulations. AAC with Glass powder content show high shrinkage values as compared to the control mix. Shrinkage is increased linearly as the percentage replacement of glass powder is increased. This phenomenon is due to the self-desiccation. As the fine aggregates used in this research are very fine quartz sand with fine glass powder. We know that by increasing percentage replacement of glass powder the fineness modulus of sand and glass powder composites drops from 1.23 to 0.79 and the water to cement ratio has been kept constant due to this effect shrinkage response is increased.

4.6. Acid Attack

The concrete being alkaline in nature makes it more vulnerable to acid attack. It is of great importance to check the behavior of concrete against acid attack when the concrete is aerated. When the acid comes in contact with the concrete matrix, it breaks down and deterioration begins. Hence the samples of AAC mixes were immersed in 5% solution of hydrochloric and sulfuric acids for 28 days, to check their performance against acid attack, in terms of weight loss. The results of AAC mixes in terms of weight loss are illustrated in figure 4.8. The results indicate that the weight loss decreased with the increase in the dosage of glass powder up to 15 % in the mix for hydrochloric and sulfuric acid. And the similar trend was observed for the water absorption of AAC

mixes. The water absorption also decreased with the increase in dosage of glass powder upto 15 % in the mix. It shows good results due to the less absorption of acid and resulted in reduced deterioration and weight loss. Hence, the decrease in weight loss may be related to the dense microstructure of AAC mixes. The minimum and maximum values of weight loss after exposure to hydrochloric acid were observed for GP15% and CT concrete mixes and were equal to 5.28% and 6% respectively. Similarly, the minimum and maximum values of weight loss after exposure to sulfuric acid were observed for GP15% and CT concrete mixes and were equal to 7% and 12.5% respectively.

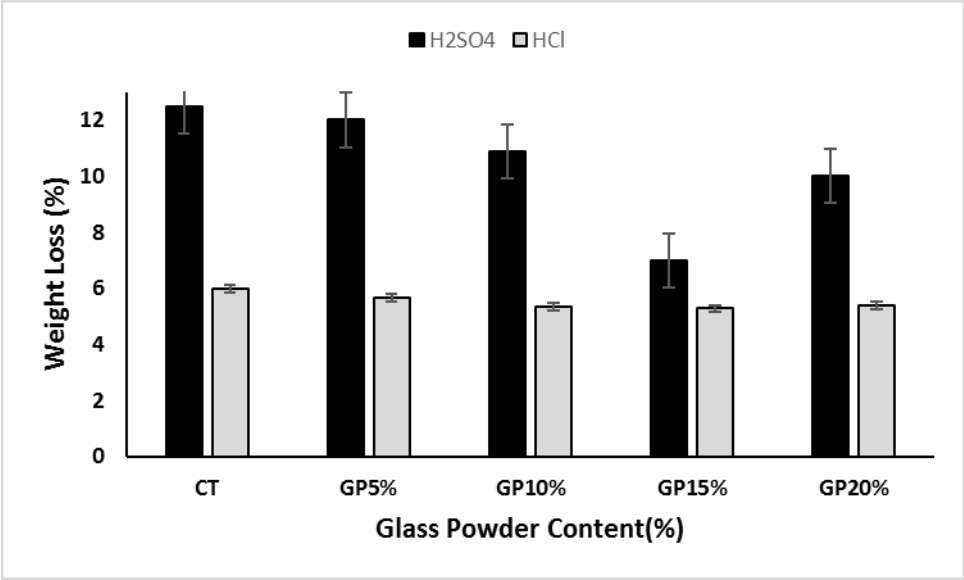

Figure 4. 8: Weight loss % of AAC mixes

4.7. Scanning Electron Microscopy of AAC

The SEM of different magnifications for the above- mentioned mixes are presented in Fig. 4.9. To analyze the microstructure of the AAC containing glass powder, scanning electron micrographs were obtained. Fig.4.9 (a,d,g) shows the SEM micrographs of hydration products formed in the control mix. In these micrographs, interconnected pores of larger size are visible, furthermore CH Crystals are abundantly scattered. In Fig. 4.9 (b,e,h) the microstructure of mix containing 15% of GP content is shown. The SEM micrograph shows the grass like tobermorite crystals which are involved in pore refinement and densifying the microstructure. Also in this case CH crystals are not visible is also testifying the Pozzolanic potential of glass powder at GP15 Fig. 4.9 (c,f,i)

shows micrograph of AAC formulation with 20% of GP content. In this micrograph the rate of growth of tobermorite crystals is slow as compared to GP15 mix.

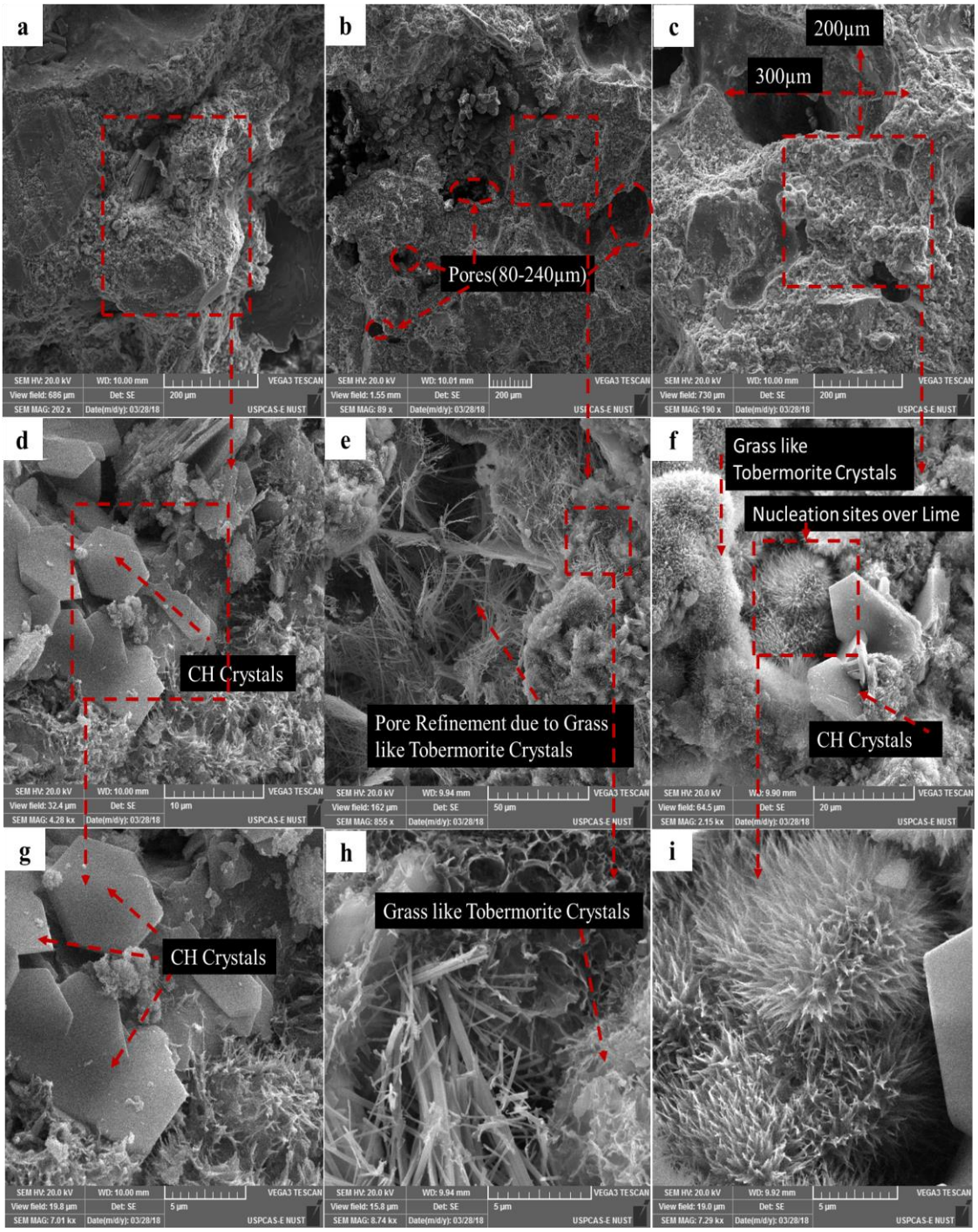

Figure 4. 9: SEM micrographs of Control mix (a,d & g),GP15 (b,e &h) and GP20 (c,f &i)

4.8. Thermogravimetric Analysis

The results for TGA analysis of CT and GP15 and GP20 are illustrated in Figure 4.10. The weight loss calculations are given in Table 4.1. According to literature three weight loss regions were observed. In the first weight loss region (110-300°C), weight loss occurs due to the loss physically and chemically attached water in CH crystals and CSH gel. In the second region (400-600°C), weight loss occurs due to the Dehydroxylation of CH crystals, in the third region (750-900 °C), the weight loss occurs due to the Decarbonation of calcium carbonate. From the table given below, the results indicate that in the first region GP20 has higher weight loss as compared to GP15 and CT mix and are equal to 25.35%, 19.31% and 19.09% respectively. Hence it showed higher rate of hydration. In the second region, the lower weight loss was observed for the GP15 as compared to GP20 and CT mix and were equal to 21.86%, 28.44% and 40.71% respectively. The results indicate that Calcium hydroxide has been consumed as a result of higher Pozzolanic activity of GP15 mix as compared to GP20 and control mixes. Hence testifying the Pozzolanic activity of glass powder. It is also justified from the compressive and flexure strength results that GP15 showed good results as compared to GP20 and CT mixes.

Table 4.1: Weight loss of AAC at 5 hours of Steam Curing

Concrete specimens	Weight loss (%)			Weight loss with respect to total weight loss (%)		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
CT	3.37	7.19	0.45	19.09	40.71	2.53
GP15%	3.35	3.79	3.07	19.31	21.86	17.68
GP20%	3.42	3.83	0.46	25.34	28.44	3.38

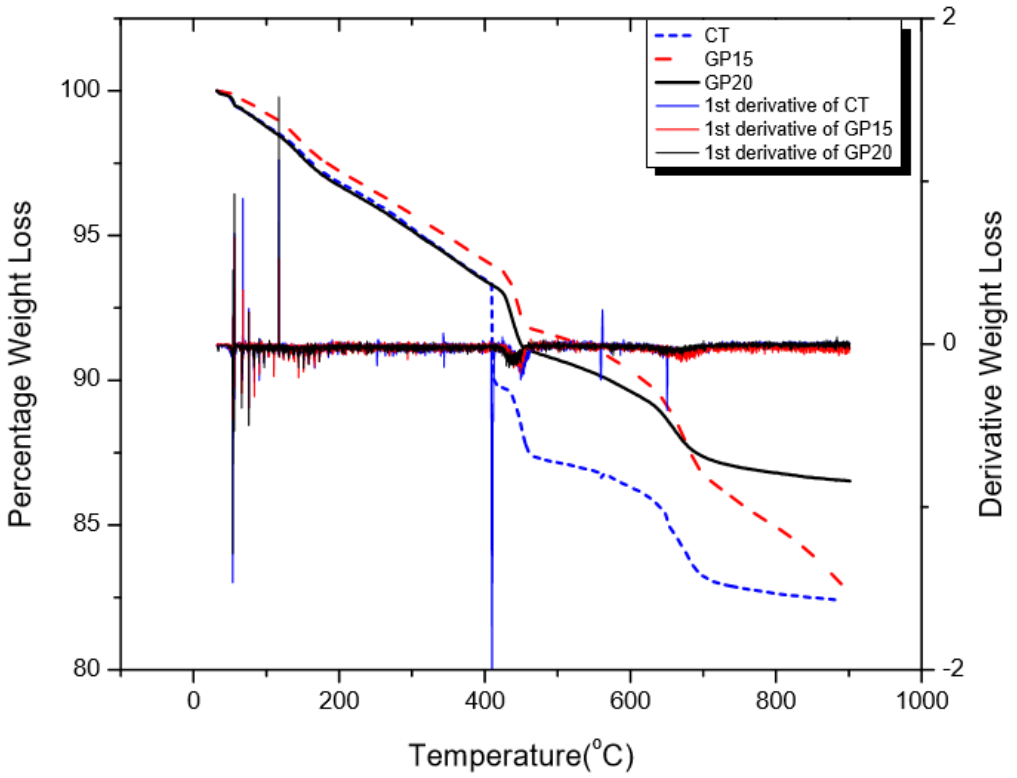

Figure 4. 10: TGA results of AAC mixes

4.9: Thermal Conductivity

Thermal conductivity results of Autoclaved aerated concrete containing control and GP mixes are shown in figure 4.11.

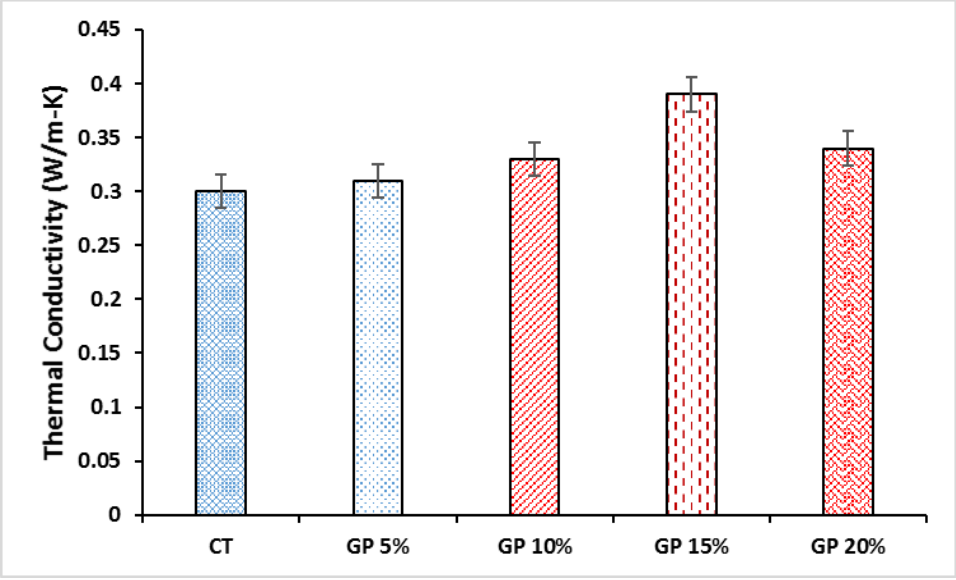

Figure 4. 11: Thermal conductivity of AAC mixes

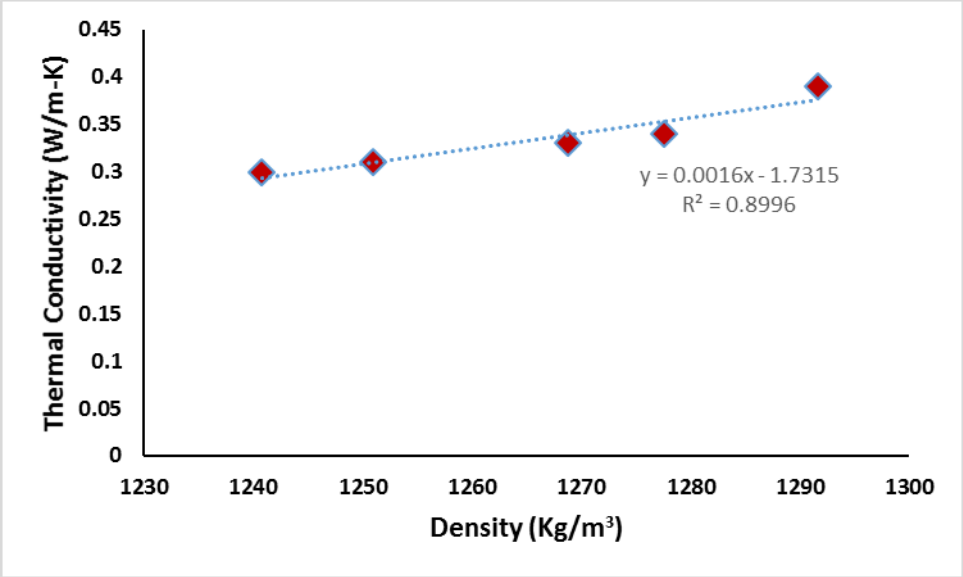

Figure 4. 12: Relationship between thermal conductivity and density

Thermal conductivity depends on many factors which consists of porosity, moisture content and unit weight. Pore sizes and their distribution in the paste matrix also effects the thermal conductivity. It also depends on the starting material used for the preparation of AAC. The results shown in figure 4.11 illustrate that the thermal conductivity increased as the percentage replacement of glass powder is increased. The maximum and minimum values of thermal conductivity were observed for GP15% and CT samples and were equal to 0.39 $Wm^{-1}k^{-1}$ and 0.3 $Wm^{-1}k^{-1}$ respectively. This increase may be related to the higher density of AAC samples as shown in figure 4.12. Thermal conductivity has direct relationship with density. These results indicated that the dense microstructure of AAC with glass powder lead to an increase in thermal conductivity of AAC.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Based on the findings of this research, the following conclusions are made;

- Shrinkage response of AAC increases with replacement percentage due to self-desiccation that is because of the more fine particles, therefore to decrease the shrinkage additional water absorption of GP should be incorporated.
- Maximum increase of 60% in compressive strength and 45% in flexure strength was observed in GP15, therefore can be used for load bearing purposes.
- Glass powder significantly enhance the CSH formation and densify the microstructure by pores refinement attributed to formation of tobermorite crystals. Furthermore, Pozzolanic potential of the glass powder is evident in TGA.
- Lower weight loss observed for HCL than sulphuric acid due to DEF. Weight loss decreases with increase in glass powder replacement.
- The thermal conductivity increased with the increase in glass powder content up to 15%. In comparison to control mix and GP15% formulations, the maximum increase in thermal conductivity was found to be 30%.

5.2. Recommendations

- It is recommended to use the blends of locally available raw materials (Granite powder, Bagasse ash, Glass powder) in AAC. Furthermore investigate the effect of steam curing on tobermorite crystals formation by varying the temperature and duration of curing

REFERENCES

1. Tan, K.H. and H. Du, *Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties.* Cement and Concrete Composites, 2013. **35**(1): p. 109-117.

2. EPA, *"Municipal solid waste generation, recycling, and disposal in the United States: facts and Figures for 2005",* , E.P. Agency, Editor. 2005.

3. Kus, H. and T. Carlsson, *Microstructural investigations of naturally and artificially weathered autoclaved aerated concrete.* Cement and Concrete Research, 2003. **33**(9): p. 1423-1432.

4. Aroni, S., *On energy conservation characteristics of autoclaved aerated concrete.* Materials and Structures, 1990. **23**(1): p. 68-77.

5. Narayanan, N. and K. Ramamurthy, *Structure and properties of aerated concrete: a review.* Cement and Concrete Composites, 2000. **22**(5): p. 321-329.

6. Dey, V., A. Bonakdar, and B. Mobasher, *Low-velocity flexural impact response of fiber-reinforced aerated concrete.* Cement and Concrete Composites, 2014. **49**: p. 100-110.

7. Brooks, M.R.M., *Thermal insulating construction materials.* Jan 2008. **Vol 2**.

8. CHAVAN P.G, M.J.R., PATIL S.B, *SUBSTANTIAL USE OF SOLID WASTE* International Journal of Advanced Technology in Civil Engineering, 2013. **Volume-2**(Issue-1).

9. Taylor, H.F.W., *Cement Chemistry*. 2nd ed ed. 1997, London: Thomas Telford. 459

10. Hema, C., *Study on cement concrete using glass powder.* Journal of chemical and pharmaceutical sciences, 2016. **Vol 9**(Issue 2).

11. Holt, E. and P. Raivio, *Use of gasification residues in aerated autoclaved concrete.* Cement and Concrete Research, 2005. **35**(4): p. 796-802.

12. Karakurt, C., H. Kurama, and İ.B. Topçu, *Utilization of natural zeolite in aerated concrete production.* Cement and Concrete Composites, 2010. **32**(1): p. 1-8.

13. Kurama, H., İ.B. Topçu, and C. Karakurt, *Properties of the autoclaved aerated concrete produced from coal bottom ash.* Journal of Materials Processing Technology, 2009. **209**(2): p. 767-773.

14. Wongkeo, W. and A. Chaipanich, *Compressive strength, microstructure and thermal analysis of autoclaved and air cured structural lightweight concrete made with coal bottom ash and silica fume.* Materials Science and Engineering: A, 2010. **527**(16): p. 3676-3684.

15. Wongkeo, W., et al., *Compressive strength, flexural strength and thermal conductivity of autoclaved concrete block made using bottom ash as cement replacement materials.* Materials & Design, 2012. **35**: p. 434-439.

16. Du, H. and K.H. Tan, *Use of waste glass as sand in mortar: Part II – Alkali–silica reaction and mitigation methods.* Cement and Concrete Composites, 2013. **35**(1): p. 118-126.

17. Du, H. and K.H. Tan, *Effect of particle size on alkali–silica reaction in recycled glass mortars.* Construction and Building Materials, 2014. **66**: p. 275-285.

18. Hamad, A.J., *Materials, Production, Properties and Application of Aerated Lightweight Concrete: Review.* International Journal of Materials Science and Engineering, 2014. **Vol. 2, No. 2**.

19. Brooks, A.M.N.a.J.J., *Concrete Technology*. second Edition ed. 2010: Prentice Hall, Pearson Education.

20. Yen, L.B., *Study of water ingress into foamed concrete*. 2006, National University of Singapore.

21. Rudolph C. Valore, Jr., *Cellular Concretes Part 1 Composition and Methods of Preparation.* Journal Proceedings. **50**(5).

22. Rudnai, G., *Lightweight concretes*. 1963: Budapest : Akademiai Kiado.

23. Kittipong Kunchariyakun, S.A., Kwannate Sombatsompop, *Propoerties of autoclaved aereted concrete incorporating rice husk ash as partial repalcement of fine aggregate.* Cement & Concrete Composites, 2015. **55**: p. 11-16.

24. Huang, X.-y., et al., *Preparation of autoclaved aerated concrete using copper tailings and blast furnace slag.* Construction and Building Materials, 2012. **27**(1): p. 1-5.

25. Pehlivanlı, Z.O., İ. Uzun, and İ. Demir, *Mechanical and microstructural features of autoclaved aerated concrete reinforced with autoclaved polypropylene, carbon, basalt and glass fiber.* Construction and Building Materials, 2015. **96**: p. 428-433.

26. Narayanan, N. and K. Ramamurthy, *Microstructural investigations on aerated concrete.* Cement and Concrete Research, 2000. **30**(3): p. 457-464.

27. kansagra, V., *"A Brief report on Autoclaved Aerated Concrete (AAC) products*.

28. Johnston, C., *Waste Glass as Coarse Aggregate for Concrete.* 1974: p. 344–350.

29. Shayan, A. and A. Xu, *Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs.* Cement and Concrete Research, 2006. **36**(3): p. 457-468.

30. M. Pattengil, a.T.C.S., *Use of ground glass as a pozzolan*, in *Albuquergue Symposium on Utilization of Waste Glass in Secondary Products*. 1973: Albuquerque, New Mexico, U.S.A. p. 137–153.

31. Girbes, I.S., C.; Lopez- Tendero, M. and Belena, I. *Recycled glass cullet as partial Portland cement replacement, Sustainable Waste Management and Recycling: Glass Waste*. in *Proceedings of the International Conference Organised by the Concrete and Masonry Research Group*. 2004. Kingston University, London (England).

32. Shi, C., et al., *Characteristics and pozzolanic reactivity of glass powders.* Cement and Concrete Research, 2005. **35**(5): p. 987-993.

33. materials, A.s.f.t.a., *ASTM C618-99 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. Annual book of ASTM standards 2000: Philadelphia.

34. Schwarz, N., H. Cam, and N. Neithalath, *Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash.* Cement and Concrete Composites, 2008. **30**(6): p. 486-496.

35. Pike, R.G., Hubbard, Donald, Newman, E S. *Binary silicate glasses in the study of alkali- aggregate reaction*. in *39th Annual Meeting of the Highway Research Board*. 1960. Washington DC, United States: Highway Research Board.

36. Terro, M.J., *Properties of concrete made with recycled crushed glass at elevated temperatures.* Building and Environment, 2006. **41**(5): p. 633-639.

37. Jin, W.M., C. and Baxter, S, *Glasscrete — concrete with glass aggregate.* ACI Materials Journal 2000: p. 208–213.

38. Taha, B. and G. Nounu, *Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement.* Construction and Building Materials, 2008. **22**(5): p. 713-720.

39. Figg, J.W. *Reaction between cement and artificial glass in concrete*. in *5th International Conference on AAR in concrete*. 1981. Cape Town, South Africa.

40. Meyer, C. and S. Baxter, *Use of recycled glass for concrete masonry blocks. Final report*. 2018.

41. Shao, Y., et al., *Studies on concrete containing ground waste glass.* Cement and Concrete Research, 2000. **30**(1): p. 91-100.

42. Shayan, A. and A. Xu, *Value-added utilisation of waste glass in concrete.* Cement and Concrete Research, 2004. **34**(1): p. 81-89.

43. Mihaljevic, S.N., *Effects of Waste Glass and Polymer Addition on the Performance of Concrete Masonry Blocks*. October 2009, McMaster University, Hamilton, Ontario, Canada.

44. materials, A.s.f.t.a., *ASTM C1260-07, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*. 2007: West Conshohocken.

45. Walczak, P., et al., *Utilization of Waste Glass in Autoclaved Aerated Concrete.* Procedia Engineering, 2015. **122**: p. 302-309.